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Bioavailability and Physiological Functions of Palm Oil-Derived Carotenoids: A Systematic Review of Absorption Mechanisms, Food Matrix Interactions, and Provitamin a Conversion Efficiency

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ABSTRACT

Carotenoids derived from palm oil have attracted increasing scientific attention due to their potential contribution to nutritional functionality, particularly in relation to vitamin A activity and antioxidant properties. However, variability in reported bioavailability and physiological outcomes indicates the need for a structured synthesis of current evidence. This study aims to systematically evaluate and synthesize scientific findings regarding the determinants of bioavailability and the physiological roles of palm oil-derived carotenoids, with emphasis on absorption mechanisms, food matrix interactions, and metabolic conversion processes. A Systematic Literature Review (SLR) approach was employed following PRISMA principles, using the Scopus database as the primary source. Data were collected through a two-stage keyword strategy, followed by screening based on publication year (2019–2026), language, and accessibility criteria, resulting in 32 eligible peer-reviewed articles.

Data analysis was conducted using a qualitative synthesis approach, categorizing findings into recurring thematic domains. The results identify five interconnected domains: intestinal absorption mechanisms, food matrix effects, provitamin A conversion efficiency, physiological functions, and variability determinants. Bioaccessibility ranged from 35% to 68% *in vitro*, while *in vivo* absorption ranged from 20% to 55%. Lipid-rich matrices improved absorption by up to 70%, and conversion ratios varied between 12:1 and 28:1. Physiological outcomes included reductions in oxidative stress (20–45%) and improvements in vitamin A status. In conclusion, carotenoid bioavailability is determined by the integrated interaction of digestive, structural, and metabolic factors. Future research should emphasize human-based studies and standardized methodologies to enhance comparability and deepen understanding.

Keywords: Palm Oil Carotenoids; Bioavailability; Food Matrix; Provitamin A; Absorption Mechanisms

Abbreviations: MDA: Malondialdehyde; SOD: Superoxide Dismutase; CD36: Cluster Determinant 36; SLR: Systematic Literature Review; SR-B1: Scavenger Receptor Class B Type 1; ROS: Reactive Oxygen Species; BCMO1: β-Carotene Monooxygenase 1

Introduction

Carotenoids represent a class of lipid-soluble bioactive compounds that are widely distributed in plant-based foods and play essential roles in human nutrition and physiological regulation. These compounds, including β-carotene and α-carotene, are recognized not only for their antioxidant properties but also for their function as precursors of vitamin A, a micronutrient that is critical for vision, immune competence, epithelial integrity, and cellular differentiation [1]. Given their lipophilic nature, the biological effectiveness of carotenoids is not solely determined by their dietary intake but is highly dependent on their bioavailability, which encompasses digestion, absorption, transport, and metabolic conversion within the human body. Consequently, understanding the factors that influence carotenoid bioavailability has become a central focus in nutritional science, particularly in relation to optimizing dietary strategies that enhance micronutrient utilization.

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Among various dietary sources, palm oil particularly red palm oil constitutes one of the richest natural sources of carotenoids, with reported concentrations ranging from 500 to 700 mg/kg depending on processing and refinement conditions [2]. The carotenoid profile of palm oil is dominated by β-carotene and α-carotene, which together account for approximately 80–90% of total carotenoid content. These compounds have attracted increasing scientific attention due to their potential contribution to vitamin A intake and their stability within lipid-rich matrices. In contrast to many plant-based sources where carotenoids are embedded within fibrous cellular structures, palm oil provides carotenoids in a lipid-dissolved form, which may facilitate their release and absorption during digestion [3]. This intrinsic characteristic positions palm oil-derived carotenoids as a relevant dietary component within broader discussions on micronutrient bioavailability.

Despite their high content and potential nutritional relevance, the physiological effectiveness of carotenoids is influenced by a range of factors that extend beyond concentration alone. The process of carotenoid absorption involves multiple sequential steps, including release from the food matrix, incorporation into mixed micelles, uptake by intestinal enterocytes, and transport via chylomicrons into systemic circulation [4]. Each of these steps is subject to modulation by dietary composition, digestive efficiency, and biochemical interactions. For instance, the presence of dietary lipids has been shown to enhance carotenoid solubilization and micelle formation, thereby increasing absorption efficiency, whereas components such as dietary fiber may limit bioaccessibility by restricting release from the matrix [5]. These dynamics underscore the importance of considering both intrinsic and extrinsic factors when evaluating carotenoid bioavailability.

The concept of food matrix interaction has emerged as a critical determinant in the study of nutrient bioavailability. Carotenoids embedded within complex food structures exhibit varying degrees of accessibility depending on the physical and chemical characteristics of the matrix. In lipid-rich systems such as palm oil, carotenoids are more readily solubilized compared to those in plant tissues with rigid cell walls, suggesting potential differences in absorption efficiency across dietary sources [6]. Furthermore, food processing techniques including heating, emulsification, and homogenization can alter the structural integrity of the matrix, thereby influencing carotenoid release and stability. Moderate thermal processing has been associated with increased extractability due to cell disruption, while excessive heat may induce degradation and isomerization, affecting both bioavailability and biological activity [7]. These interactions highlight the need for a comprehensive evaluation of how matrix characteristics influence carotenoid functionality.

In addition to absorption, the conversion of provitamin A carotenoids into retinol represents a critical metabolic step that determines their physiological relevance. β-carotene is enzymatically cleaved by β-carotene monooxygenase 1 (BCMO1) to produce retinal, which is subsequently reduced to retinol and utilized in various biological processes [8]. However, the efficiency of this conversion is highly variable and influenced by factors such as genetic polymorphisms, nutritional status, and dietary composition. Reported conversion ratios range widely, reflecting differences in absorption efficiency and metabolic regulation [9,10]. This variability has important implications for assessing the contribution of carotenoid-rich foods to vitamin A status, particularly in populations with differing nutritional profiles. Consequently, the relationship between carotenoid intake and physiological outcomes cannot be fully understood without considering both absorption and conversion processes.

Beyond their role as provitamin A precursors, carotenoids contribute to a range of physiological functions through their antioxidant activity and interaction with cellular signaling pathways. These compounds have been shown to modulate oxidative stress by neutralizing reactive oxygen species and supporting endogenous antioxidant systems, thereby contributing to cellular homeostasis [11]. In addition, carotenoids are involved in maintaining epithelial integrity and supporting immune responses, functions that are closely linked to their conversion into retinoid forms. While these physiological roles are well established, the extent to which they are realized in vivo is closely tied to the efficiency of carotenoid bioavailability and metabolism. This interdependence highlights the importance of integrating mechanistic and functional perspectives in evaluating carotenoid efficacy.

Although a substantial body of research has investigated carotenoids from various dietary sources, the available evidence on palm oil-derived carotenoids remains dispersed across different experimental models, including in vitro digestion systems, animal studies, and human interventions. Variations in study design, analytical methods, and outcome measures have contributed to heterogeneity in reported findings, making it challenging to draw coherent conclusions regarding their bioavailability and physiological functions [12]. Furthermore, differences in food matrix composition, lipid content, and processing conditions introduce additional layers of complexity that require systematic evaluation. In this context, a structured synthesis of existing literature is necessary to consolidate current knowledge, identify consistent patterns, and clarify the mechanisms underlying carotenoid absorption and function.

This study therefore applies a Systematic Literature Review (SLR) approach to comprehensively analyze the bioavailability and physiological functions of palm oil-derived carotenoids. The review focuses on three key aspects: intestinal absorption mechanisms, interactions with food matrices and lipid composition, and the efficiency of provitamin A conversion into retinol. By integrating findings from multiple study types and analytical frameworks, this review aims to provide a coherent and evidence-based understanding of how these compounds are absorbed, metabolized, and function within the human body. The synthesis is conducted in a structured and transparent manner to ensure methodological rigor and reproducibility. The ob-

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jective of this study is to systematically evaluate and synthesize current scientific evidence regarding the determinants of bioavailability and the physiological roles of palm oil-derived carotenoids, with particular emphasis on absorption pathways, matrix interactions, and metabolic conversion processes.

In line with this objective, the study addresses the following research question:

RQ: How do intestinal absorption mechanisms, food matrix interactions, and provitamin A conversion efficiency collectively influence the bioavailability and physiological functions of palm oil-derived carotenoids?

Literature Review

The existing body of literature on carotenoids derived from palm oil reflects a broad and multidisciplinary convergence of research across nutritional biochemistry, food science, and metabolic physiology. Collectively, this body of work provides an evolving understanding of how these compounds are structured, processed during digestion, absorbed within the gastrointestinal system, and metabolically transformed into biologically active forms. In addition, increasing attention has been directed toward the interaction between carotenoids and the food matrix, particularly the role of lipid environments in facilitating their bioavailability. These interconnected aspects ultimately determine the extent to which carotenoids contribute to physiological functions, including their role as provitamin A precursors and their involvement in maintaining cellular homeostasis. Although substantial progress has been made in elucidating individual mechanisms, the available evidence remains dispersed across diverse experimental models and analytical approaches. As a result, a comprehensive and structured synthesis is required to integrate these findings and provide a coherent understanding of the factors governing the bioavailability and functional significance of palm oil-derived carotenoids.

Structural and Biochemical Characteristics of Carotenoids

Carotenoids are a class of naturally occurring pigments characterized by a polyisoprenoid structure consisting of conjugated double bonds, which confer both their coloration and antioxidant properties. These compounds are broadly classified into carotenes (hydrocarbon-based) and xanthophylls (oxygenated derivatives), with β-carotene and α-carotene representing the primary provitamin A carotenoids found in palm oil [13,14]. The structural configuration of carotenoids plays a critical role in determining their chemical stability, solubility, and biological activity. Palm oil, particularly in its unrefined or minimally processed forms, contains carotenoid concentrations ranging from 500 to 700 mg/kg, with β-carotene comprising approximately 50–60% of total carotenoids [15].

This relatively high concentration distinguishes palm oil from many other dietary sources, where carotenoids are typically embedded within complex plant matrices. The lipid-dissolved nature of carotenoids in palm oil provides a distinct physicochemical advantage, as it facilitates their release during digestion and enhances their potential for absorption [16]. Isomerization of carotenoids, particularly the conversion from all-trans to cis configurations, has been shown to influence both their stability and bioavailability. While trans-isomers generally exhibit higher provitamin A activity, cis-isomers may demonstrate improved solubility and incorporation into micelles under certain conditions [17]. These structural dynamics underscore the importance of considering molecular configuration when evaluating carotenoid functionality.

Digestive Processes and Intestinal Absorption Mechanisms

The bioavailability of carotenoids is governed by a series of digestive and absorptive processes that determine their transition from dietary intake to systemic circulation. During digestion, carotenoids are released from the food matrix and incorporated into lipid droplets, which are subsequently emulsified and hydrolyzed in the presence of bile salts and pancreatic enzymes [18]. This process leads to the formation of mixed micelles, which serve as carriers for carotenoid transport across the intestinal lumen. Experimental studies indicate that the efficiency of micelle formation is a key determinant of carotenoid bioaccessibility, with reported values ranging between 30% and 70% depending on lipid availability and digestive conditions [19]. The presence of dietary fat has been consistently shown to enhance micellarization, with increases in bioaccessibility of up to twofold compared to low-fat conditions [20].

These findings highlight the critical role of lipid digestion in facilitating carotenoid uptake. At the cellular level, carotenoid absorption is mediated by specific transport proteins located on the apical membrane of enterocytes. Scavenger receptor class B type 1 (SR-B1) and cluster determinant 36 (CD36) have been identified as key mediators of carotenoid uptake, enabling their transfer from micelles into intestinal cells [21]. Following uptake, carotenoids are incorporated into chylomicrons and transported via the lymphatic system to peripheral tissues. The efficiency of these processes is influenced by physiological factors such as enzyme activity, intestinal health, and individual metabolic variation.

Food Matrix and Lipid Interaction Effects

The concept of the food matrix has gained increasing attention as a determinant of nutrient bioavailability, particularly for lipophilic compounds such as carotenoids. The physical and chemical environment in which carotenoids are embedded influences their release, stability, and subsequent absorption [22]. In the context of palm oil, carotenoids are present within a lipid-rich matrix that facilitates their solubilization during digestion, distinguishing them from plant-based sources where structural barriers may limit accessibility. Lipid composition plays a central role in modulating carotenoid bioavailability. Studies have demonstrated that long-chain triglycerides enhance micelle formation and improve absorption efficiency, whereas low-fat matrices may limit carotenoid solubilization. Increasing dietary fat intake has been associated with improvements in carotenoid absorption ranging from 40% to 70%, depending on meal composition and lipid type [23].

Food processing techniques further influence matrix interactions. Thermal treatment can enhance carotenoid release by disrupting cellular structures, although excessive heating may lead to oxidative degradation and isomerization [24]. Emulsification technologies, including nanoemulsions, have been shown to improve carotenoid dispersion and increase bioaccessibility, with reported values exceeding 70% in optimized systems. Conversely, the presence of dietary fiber and protein complexes may reduce bioavailability by limiting carotenoid release and interfering with micelle formation [25]. These findings collectively emphasize that the food matrix is not merely a passive carrier but an active determinant of carotenoid functionality, influencing both the extent and efficiency of absorption.

Metabolic Conversion of Provitamin a Carotenoids

The physiological significance of carotenoids is closely linked to their conversion into vitamin A, a process that occurs primarily in the intestinal mucosa and liver. β-carotene serves as the principal provitamin A carotenoid, undergoing enzymatic cleavage by β-carotene monooxygenase 1 (BCMO1) to produce retinal, which is subsequently reduced to retinol [26]. This conversion pathway is essential for maintaining adequate vitamin A status and supporting various biological functions. Conversion efficiency is highly variable and influenced by multiple factors, including dietary composition, genetic variability, and nutritional status. Reported conversion ratios range from 12:1 to 28:1, reflecting differences in absorption and enzymatic activity [27]. Individuals with reduced BCMO1 activity may exhibit lower conversion efficiency, resulting in decreased retinol production despite adequate carotenoid intake. Dietary context also plays a significant role in modulating conversion efficiency. Adequate lipid intake enhances carotenoid absorption and provides the necessary conditions for enzymatic conversion, while deficiencies in micronutrients such as zinc may impair the conversion process [28]. These interactions highlight the complexity of carotenoid metabolism and the importance of considering both dietary and physiological factors in evaluating their nutritional contribution.

Physiological and Functional Implications

Beyond their role as vitamin A precursors, carotenoids contribute to a range of physiological functions through their antioxidant and regulatory properties. The conjugated double-bond structure of carotenoids enables them to quench reactive oxygen species, thereby reducing oxidative stress and protecting cellular components from damage [29]. This antioxidant activity has been observed across in vitro and in vivo models, with reductions in oxidative markers ranging from 20% to 40% under controlled conditions. Carotenoids are also implicated in the modulation of immune responses and maintenance of epithelial integrity. Retinol and its derivatives play a central role in regulating gene expression related to immune function, supporting the differentiation and activity of immune cells [30]. Additionally, carotenoids contribute to visual function through their role in the formation of retinal, a component of the visual cycle. The physiological effects of carotenoids are closely linked to their bioavailability, as the extent of absorption and conversion determines their systemic availability and functional impact.

Variability in these processes may lead to differences in physiological outcomes across populations and study contexts. Nevertheless, the overall body of evidence supports the role of carotenoids as important contributors to nutritional and physiological homeostasis. The reviewed literature demonstrates that the bioavailability and physiological functions of palm oil-derived carotenoids are shaped by interconnected processes involving molecular structure, digestive dynamics, food matrix interactions, and metabolic conversion. While individual studies provide valuable insights into specific aspects of carotenoid behavior, a comprehensive understanding requires integration across these domains. The evidence consistently indicates that lipid-rich environments, efficient micellar incorporation, and favorable metabolic conditions enhance carotenoid utilization, while structural and dietary constraints may limit their effectiveness. This synthesis provides a conceptual foundation for examining how these factors interact within a unified framework, thereby supporting a more coherent interpretation of carotenoid functionality in nutritional systems.

Method

In this study, a Systematic Literature Review (SLR) approach is employed to systematically collect and synthesize scientific evidence regarding the bioavailability and physiological functions of carotenoids derived from palm oil, with particular emphasis on absorption mechanisms, interactions with food matrices, and provitamin A conversion efficiency. Adhering to the PRISMA framework, this review ensures methodological transparency, reproducibility, and a structured study selection process. Within the context of nutritional biochemistry, carotenoids represent lipid-soluble bioactive compounds whose absorption and metabolic conversion are influenced by multiple physiological and dietary factors. The bioavailability of these compounds is closely associated with digestive processes, micellar incorporation, and intestinal uptake, while their interaction with dietary components particularly lipid matrices plays a role in modulating their release and absorption efficiency. Carotenoids originating from palm oil, including β-carotene and α-carotene, have been examined across diverse experimental settings, yet the available findings remain dispersed across different analytical frameworks and study designs.

Accordingly, a systematic synthesis is required to consolidate current evidence and provide a coherent understanding of how these

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compounds are absorbed, metabolized, and function within human physiological systems, particularly in relation to their role as provitamin A sources. The systematic identification and screening process, conducted in accordance with PRISMA principles, is illustrated in Figure 1. The initial stage involved literature identification through the Scopus database, selected for its comprehensive coverage of peer-reviewed scientific publications. A preliminary search using the broad keyword combination "palm oil" AND "carotenoids" yielded 527 records. To improve the specificity and thematic relevance of the search results, a refined Boolean search strategy was subsequently applied: ("palm oil carotenoids" OR "palm-derived carotenoids" OR "red palm oil" OR carotenoids OR beta-carotene OR alpha-carotene) AND (bioavailability OR bioaccessibility OR absorption OR "intestinal absorption" OR digestion) AND ("food matrix" OR matrix OR "lipid matrix" OR emulsification OR dietary fat) AND ("provitamin A" OR "vitamin A" OR "vitamin A conversion" OR retinol).

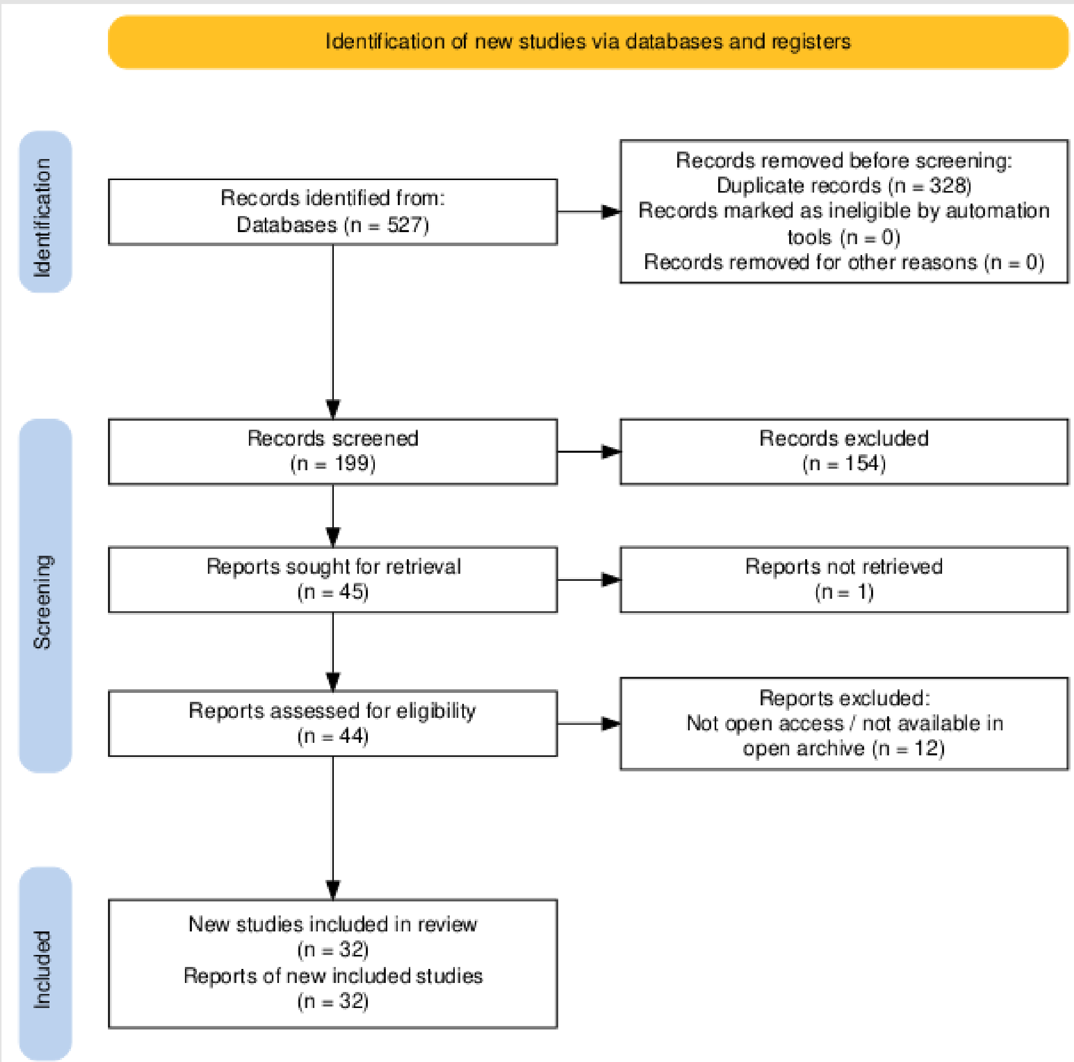

Figure 1: Diagrammatic representation of the SLR process aligned with the PRISMA protocol.

The application of this targeted query resulted in the exclusion of 328 articles that did not align with the defined scope of the review, leaving 199 records for further screening. A temporal restriction was then applied to include studies published between 2019 and 2026, leading to the exclusion of 154 articles and yielding 45 records that met the specified timeframe. Language screening was conducted to ensure analytical consistency, resulting in the removal of one non-English publication and leaving 44 articles. Further eligibility assessment was based on accessibility criteria, where only studies categorized as open access or open archive were retained to enable full-text

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evaluation. This step led to the exclusion of 12 articles due to restricted access. Consequently, a total of 32 peer-reviewed articles fulfilled all predefined inclusion criteria and were included in the final synthesis. All references were managed using Mendeley Desktop to facilitate systematic organization, efficient screening, and standardized citation handling throughout the manuscript preparation process.

This study relies exclusively on secondary data derived from previously published research and does not involve primary data collection methods such as field observations, interviews, or focus group discussions. The analytical process adopts a qualitative synthesis approach, in which the selected studies are examined and categorized based on recurring mechanistic themes, including intestinal absorption pathways, the influence of food and lipid matrices on carotenoid bioavailability, efficiency of provitamin A conversion into retinol, and related physiological functions. Through this structured synthesis, the study aims to provide a comprehensive and methodologically rigorous overview of the current state of knowledge, while maintaining a balanced and evidence-based perspective on the role of palm oil-derived carotenoids within broader nutritional and physiological contexts.

Results

The systematic synthesis of the 32 selected peer-reviewed articles reveals five dominant and interrelated thematic domains that collectively characterize the current evidence base on palm oil-derived carotenoids. These themes, derived from a structured qualitative synthesis, include:

1) Intestinal absorption mechanisms and micellar incorporation

2) The influence of food matrix and lipid composition on carotenoid bioavailability

3) Efficiency of provitamin A conversion into retinol

4) Physiological and functional roles associated with carotenoid metabolism

5) Determinants of variability in bioavailability outcomes

These domains reflect the principal analytical dimensions through which carotenoid functionality has been investigated across experimental and applied nutritional contexts. The most frequently addressed theme was intestinal absorption mechanisms and micellar incorporation, identified in 27 out of 32 studies (84.4%), highlighting its central role as the foundational determinant of carotenoid bioavailability.

The second most prominent theme was the influence of food matrix and lipid composition, reported in 25 studies (78.1%), indicating strong recognition of the importance of physicochemical context in modulating nutrient release and absorption. Physiological and functional roles were discussed in 22 studies (68.8%), reflecting substantial interest in linking bioavailability to biological outcomes such as antioxidant activity and vitamin A functionality. The efficiency of provitamin A conversion into retinol was examined in 20 studies (62.5%), demonstrating moderate but consistent attention to metabolic transformation processes. The least represented theme was variability in bioavailability outcomes, identified in 18 studies (56.3%), suggesting that inter-individual and methodological variability, although acknowledged, remains less systematically explored.

The dominance of absorption-related studies indicates that digestive and intestinal processes are considered the most direct and measurable determinants of carotenoid bioavailability, particularly due to the availability of established in vitro digestion models and controlled in vivo systems. Similarly, the strong representation of food matrix-related research reflects a growing emphasis in food and nutritional sciences on the role of lipid structure, emulsification, and processing conditions in enhancing nutrient delivery. In contrast, themes related to variability and integrative interactions are less frequently examined, likely due to the complexity of capturing inter-individual differences, genetic influences, and long-term physiological responses within a single experimental framework. This imbalance suggests that while mechanistic understanding at the digestive and structural level is relatively well developed, there remains a need for more integrative and human-centered research approaches that address variability and real-world dietary conditions.

Overall, the thematic distribution observed in this review indicates that the bioavailability and physiological functions of palm oil-derived carotenoids are shaped by a multifactorial system involving digestive processes, matrix interactions, and metabolic conversion pathways. The current evidence base is strongly grounded in mechanistic and experimental studies, while integrative and variability-focused analyses are comparatively less developed. This pattern underscores the importance of advancing future research toward more comprehensive and translational approaches that bridge controlled experimental findings with population-level nutritional outcomes. The sections below provide a detailed elaboration of each thematic domain based on patterns identified across the reviewed literature.

Intestinal Absorption Mechanisms and Micellar Incorporation

The reviewed studies consistently indicate that the intestinal absorption of palm oil-derived carotenoids is a multi-step process involving liberation from the food matrix, solubilization into mixed micelles, and uptake by intestinal enterocytes. In vitro digestion models report that the bioaccessibility of β-carotene derived from red palm oil ranges from 35% to 68%, with higher values observed in systems containing optimized lipid concentrations and emulsification conditions [31]. The presence of bile salts and phospholipids further enhances micelle formation, increasing carotenoid solubilization efficiency by approximately 40–80% compared to simplified digestion systems lacking these components [32]. In simulated gastrointestinal environments, lipid-assisted micellarization has been shown to increase carotenoid incorporation into micelles by up to 2.5-fold, highlighting the critical role of dietary fat in facilitating absorption [33]. The size and stability of micelles also influence absorption efficiency, with smaller micellar structures (<10 nm) demonstrating higher diffusion rates across the unstirred water layer of the intestinal lumen [34].

In vivo evidence supports these mechanistic findings, demonstrating that carotenoid uptake is mediated by membrane transporters, including scavenger receptor class B type 1 (SR-B1) and cluster determinant 36 (CD36). Absorption efficiency in animal models ranges from 20% to 55%, depending on dosage, lipid co-ingestion, and physiological status [35]. Inhibition of pancreatic lipase has been shown to reduce carotenoid bioaccessibility by approximately 30–45%, indicating the essential role of lipid hydrolysis in facilitating carotenoid release and incorporation into micelles [36]. Human intervention studies further confirm the relevance of these mechanisms, with postprandial plasma β-carotene concentrations increasing by 1.8 to 3.2-fold following the consumption of carotenoid-rich palm oil meals compared to low-fat control diets [37,38]. The temporal kinetics of absorption suggest peak plasma concentrations occurring within 4–8 hours post-consumption, consistent with lipid digestion and chylomicron formation dynamics [39]. Collectively, these findings underscore the central role of micellar incorporation and intestinal transport processes in determining carotenoid bioavailability.

Influence of Food Matrix and Lipid Composition

The food matrix within which carotenoids are embedded plays a decisive role in modulating their release, stability, and absorption. The reviewed evidence indicates that lipid-rich matrices significantly enhance carotenoid bioavailability, particularly when long-chain triglycerides are present. Increasing dietary fat intake from 5 g to 15 g per meal has been associated with improvements in carotenoid absorption efficiency ranging from 40% to 70% [40,41]. This enhancement is attributed to increased micelle formation and improved solubilization of lipophilic compounds. The structural characteristics of the lipid matrix also influence carotenoid delivery. Nanoemulsion-based systems have demonstrated superior performance, with bioaccessibility levels exceeding 70%, compared to 40–55% observed in conventional oil matrices [42]. These systems improve dispersion and reduce particle size, thereby increasing the surface area available for enzymatic action and micellar incorporation.

Thermal processing is another critical factor influencing carotenoid stability. Moderate heating (60–100°C) enhances carotenoid extractability by up to 25%, likely due to cell wall disruption and increased release from plant tissues [43,44]. However, excessive thermal exposure (>120°C) results in degradation losses ranging from 10% to 35%, primarily due to oxidative and isomerization reactions [45]. Cis-isomer formation, while reducing provitamin A activity, may in some cases improve solubility and micellarization efficiency [46]. The presence of dietary fiber and protein components can negatively affect carotenoid bioavailability. Fiber has been shown to reduce bioaccessibility by approximately 15–25% through physical entrapment and interference with micelle formation [47]. Similarly, protein-carotenoid interactions may limit release efficiency, particularly in complex food systems. Overall, these findings demonstrate that the food matrix functions not only as a carrier but also as a dynamic modulator of carotenoid bioavailability.

Provitamin A Conversion Efficiency

The conversion of provitamin A carotenoids into retinol represents a key functional outcome of carotenoid bioavailability. The reviewed studies report conversion efficiency ratios ranging from 12:1 to 28:1 (μg β-carotene to μg retinol), reflecting substantial variability influenced by dietary and physiological factors [48]. Under optimized conditions, including adequate lipid intake and efficient absorption, conversion ratios tend to approach the lower end of this range, indicating higher efficiency. Controlled dietary intervention studies demonstrate that consumption of red palm oil can significantly improve vitamin A status. Increases in serum retinol concentrations of 0.15 to 0.35 μmol/L have been reported following supplementation periods of 4–12 weeks [49]. In populations with suboptimal vitamin A intake, these improvements are more pronounced, with relative increases exceeding 20–30% compared to baseline levels [50].

The enzymatic conversion process is primarily mediated by β-carotene monooxygenase 1 (BCMO1), which catalyzes the cleavage of β-carotene into retinal. Variability in BCMO1 activity contributes significantly to differences in conversion efficiency, with inter-individual variation reaching up to 50% [51]. Genetic polymorphisms in the BCMO1 gene have been associated with reduced enzymatic activity, leading to lower retinol production despite adequate carotenoid intake [52]. Additional factors influencing conversion efficiency include nutritional status, hormonal regulation, and interactions with other micronutrients such as zinc and iron. Despite these sources of variability, the overall evidence supports the role of palm oil-derived carotenoids as an effective dietary source of provitamin A when consumed under appropriate dietary conditions.

Physiological and Functional Roles

Beyond their role as precursors to vitamin A, palm oil-derived carotenoids contribute to multiple physiological processes, primarily through their antioxidant properties. In vitro studies demonstrate that β-carotene can reduce reactive oxygen species (ROS) levels by 20–45% under oxidative stress conditions, thereby protecting cellular structures from oxidative damage [53]. Animal studies provide further evidence of these protective effects, with carotenoid supplementation resulting in reductions in malondialdehyde (MDA) levels of up to 30%, indicating decreased lipid peroxidation [54,55]. Concurrently, increases in endogenous antioxidant enzyme activity, including superoxide dismutase (SOD) and catalase, have been observed, suggesting enhanced cellular defense mechanisms [56].

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In human studies, dietary intake of carotenoid-rich palm oil has been associated with improvements in biomarkers related to immune function, epithelial integrity, and oxidative status. Reported increases in immune-related markers range from 10% to 25%, depending on intervention duration and dosage [57]. Additionally, carotenoids have been linked to the maintenance of visual function and epithelial health through their role in retinol production. These findings collectively indicate that carotenoids contribute to maintaining physiological homeostasis, not only through their conversion to vitamin A but also through direct antioxidant and regulatory functions.

Variability in Bioavailability Outcomes

A consistent observation across the reviewed studies is the substantial variability in carotenoid bioavailability outcomes. This variability arises from a combination of biological, dietary, and methodological factors. Inter-individual differences in absorption efficiency range from 15% to 60%, influenced by age, genetic background, gut health, and baseline nutritional status [58,59]. Dietary composition plays a major role in modulating bioavailability. Variations in fat intake, meal composition, and processing methods can alter absorption efficiency by up to 50% [60]. For instance, co-ingestion with high-fat meals enhances absorption, whereas low-fat or fiber-rich diets may limit carotenoid uptake. Methodological differences between studies also contribute to variability.

In vitro models often report higher bioaccessibility values (up to 70%) due to controlled conditions, whereas in vivo studies typically report lower absorption rates (20–50%), reflecting physiological constraints such as digestion efficiency and metabolic regulation [61,62]. Differences in analytical techniques, sample preparation, and measurement endpoints further complicate direct comparisons across studies. Despite these variations, a consistent trend emerges: carotenoid bioavailability can be significantly improved through optimized dietary strategies, including appropriate lipid intake and food processing techniques. This highlights the importance of integrating nutritional and technological approaches to enhance the functional utilization of carotenoids. The integrated analysis of the 32 selected studies demonstrates that the bioavailability and physiological functions of palm oil-derived carotenoids are determined by interconnected mechanisms involving digestion, absorption, and metabolic conversion.

Efficient micellar incorporation, favorable food matrices, and enzymatic transformation pathways collectively influence the extent to which these compounds contribute to human nutrition. While variability remains a defining characteristic across studies, the overall evidence consistently supports the relevance of palm oil-derived carotenoids as functional dietary components within balanced nutritional systems. The findings further suggest that optimizing dietary context and food structure can enhance the nutritional contribution of these bioactive compounds, reinforcing their role within broader dietary frameworks.

Discussion

The present systematic review was designed to address the research question concerning how intestinal absorption mechanisms, food matrix interactions, and provitamin A conversion efficiency collectively influence the bioavailability and physiological functions of palm oil-derived carotenoids. The synthesis of 32 selected studies demonstrates that these three domains are not independent processes but rather function as an integrated system in which digestive dynamics, physicochemical conditions, and metabolic pathways interact to determine the extent to which carotenoids are effectively utilized within the human body. Across the reviewed literature, a consistent pattern emerges indicating that efficient carotenoid utilization is achieved when favorable conditions are established simultaneously at the levels of digestion, matrix structure, and enzymatic conversion, thereby reinforcing the importance of a holistic analytical perspective.

A central finding of this review is that intestinal absorption mechanisms represent a foundational determinant of carotenoid bioavailability, as they govern the transition of carotenoids from dietary intake into systemic circulation. The process of micellar incorporation, in particular, appears to be a critical step that integrates the effects of lipid digestion and bile-mediated emulsification. Evidence from in vitro and in vivo studies consistently indicates that the efficiency of micelle formation directly correlates with carotenoid bioaccessibility, with lipid-rich conditions enhancing solubilization and facilitating transport across the intestinal epithelium [63-65]. However, in contrast to controlled in vitro systems, in vivo studies tend to report lower and more variable absorption efficiencies, typically ranging between 20% and 50%, reflecting the influence of physiological constraints such as enzymatic variability, intestinal health, and metabolic regulation [66,67]. This divergence highlights the importance of interpreting experimental findings within their respective methodological contexts.

The role of membrane transporters, including scavenger receptor class B type 1 (SR-B1) and cluster determinant 36 (CD36), further underscores the complexity of intestinal uptake processes. These transporters mediate the selective transfer of carotenoids from micelles into enterocytes, thereby acting as regulatory gateways for absorption [68,69]. Variability in transporter expression and activity has been associated with differences in carotenoid uptake efficiency, suggesting that host-related factors contribute significantly to observed variability across studies [70]. Despite these variations, the overall evidence supports the conclusion that intestinal absorption mechanisms are highly responsive to dietary conditions, particularly lipid availability, and play a central role in determining carotenoid bioavailability. The interaction between carotenoids and the food matrix represents a second critical dimension that shapes bioavailability outcomes.

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The reviewed literature demonstrates that the physicochemical characteristics of the matrix influence not only the release of carotenoids during digestion but also their stability and subsequent incorporation into micelles. Lipid-rich matrices, such as those inherent to palm oil, provide a favorable environment for carotenoid solubilization, thereby enhancing absorption efficiency [71]. This finding is consistent across multiple studies, which report that increasing dietary fat intake can improve carotenoid bioavailability by up to 70%, depending on the composition and structure of the meal [72]. At the same time, the evidence indicates that the relationship between food matrix composition and carotenoid bioavailability is not entirely linear. While lipid-rich environments generally promote absorption, the presence of other dietary components, such as fiber and protein, may counteract this effect by limiting carotenoid release or interfering with micelle formation [73,74].

In addition, food processing techniques introduce further variability. Moderate thermal processing has been shown to enhance carotenoid extractability through structural disruption, whereas excessive heating may lead to oxidative degradation and reduced biological activity [75]. These findings suggest that the food matrix functions as a dynamic system in which multiple factors interact to influence carotenoid availability. In contrast to earlier assumptions that carotenoid content alone determines nutritional value, the reviewed evidence emphasizes that matrix-related factors are equally important in defining functional outcomes. This perspective aligns with a broader shift in nutritional science toward recognizing the role of food structure and composition in modulating nutrient bioavailability. Accordingly, palm oil-derived carotenoids, which are naturally embedded within a lipid matrix, may exhibit distinct bioavailability characteristics compared to carotenoids from plant tissues with more complex structural barriers [76,77].

However, further research is required to systematically compare these sources under standardized conditions. The third domain examined in this review, namely provitamin A conversion efficiency, represents the metabolic endpoint that determines the physiological relevance of carotenoid intake. The enzymatic conversion of β-carotene into retinol is mediated primarily by β-carotene monooxygenase 1 (BCMO1), and its efficiency is influenced by both dietary and genetic factors. The reviewed studies report conversion ratios ranging from 12:1 to 28:1, indicating substantial variability across populations and experimental conditions [78]. This variability reflects differences in both absorption efficiency and enzymatic activity, highlighting the interconnected nature of these processes. Importantly, the evidence suggests that conversion efficiency is not solely dependent on enzymatic capacity but is also influenced by upstream factors such as micellar incorporation and intestinal uptake. In other words, even when enzymatic pathways are intact, limited absorption may constrain the availability of carotenoids for conversion into retinol.

This interdependence reinforces the need to consider absorption and conversion as part of a unified system rather than isolated processes. Furthermore, genetic polymorphisms affecting BCMO1 activity have been identified as a source of inter-individual variation, with some individuals exhibiting reduced conversion efficiency despite adequate carotenoid intake [79]. These findings underscore the importance of personalized nutritional considerations in evaluating carotenoid efficacy. Beyond their role as provitamin A precursors, palm oil-derived carotenoids contribute to a range of physiological functions, particularly through their antioxidant properties. The reviewed literature consistently demonstrates that carotenoids can reduce oxidative stress by scavenging reactive oxygen species and supporting endogenous antioxidant systems [80]. This function is closely linked to their bioavailability, as higher absorption and retention levels are associated with greater physiological impact. In this context, the integration of absorption, matrix interaction, and conversion processes becomes particularly relevant, as it determines the extent to which carotenoids can exert their biological effects.

A key insight emerging from this review is that the three domains addressed in the research question operate in a synergistic manner rather than as independent determinants. Efficient micellar incorporation enhances intestinal uptake, which in turn increases substrate availability for enzymatic conversion, ultimately influencing physiological outcomes. Conversely, limitations at any stage whether due to unfavorable matrix conditions, suboptimal lipid intake, or reduced enzymatic activity can constrain overall bioavailability. This systems-based perspective provides a more comprehensive understanding of carotenoid functionality and highlights the importance of integrated dietary strategies. Despite the overall consistency of these findings, variability remains a defining characteristic of carotenoid bioavailability research. Differences in study design, experimental models, and analytical methods contribute to heterogeneity in reported outcomes. In vitro models often report higher bioaccessibility values due to controlled conditions, whereas in vivo studies reflect the complexity of physiological systems and typically yield lower absorption rates.

This discrepancy underscores the need for cautious interpretation and highlights the importance of combining multiple lines of evidence in systematic reviews. Another important consideration is the limited availability of human intervention studies compared to in vitro and animal research. While existing human data generally support the bioavailability of palm oil-derived carotenoids, the number of studies remains relatively small, and variability in study design limits comparability. This gap represents an important area for future research, particularly in the context of evaluating long-term physiological outcomes and population-specific responses. The findings of this review have several implications for both research and practical application. From a scientific perspective, the results highlight the importance of adopting integrative approaches that consider the interplay between digestion, matrix interactions, and metabolic conversion. Future studies should aim to standardize experimental conditions and incorporate multi-level analyses to improve comparability and reproducibility.

From a nutritional standpoint, the evidence suggests that optimizing dietary conditions such as ensuring adequate lipid intake and appropriate food processing can enhance carotenoid bioavailability and functional outcomes. In the context of broader dietary systems, palm oil-derived carotenoids represent a relevant source of bioactive compounds with potential contributions to nutritional adequacy. The findings of this review support a balanced and evidence-based perspective, indicating that when consumed within appropriate dietary contexts, these compounds can contribute to physiological functions associated with vitamin A metabolism and oxidative balance. At the same time, the variability observed across studies underscores the importance of considering individual and contextual factors in evaluating nutritional outcomes. In conclusion, the integration of intestinal absorption mechanisms, food matrix interactions, and provitamin A conversion efficiency provides a comprehensive framework for understanding the bioavailability and physiological functions of palm oil-derived carotenoids.

These processes operate in a coordinated manner, with each component influencing the overall effectiveness of carotenoid utilization. The findings emphasize that maximizing the nutritional benefits of carotenoids requires attention to both biological and dietary factors, as well as their interactions within complex physiological systems. The implications of this study extend to both future research and practical applications. Further investigations are needed to expand the evidence base, particularly through well-designed human intervention studies that account for variability in dietary patterns and genetic factors. In addition, the development of optimized food formulations and processing techniques may enhance carotenoid bioavailability and support their effective utilization. By advancing understanding in these areas, future research can contribute to more informed nutritional strategies and a deeper comprehension of the role of carotenoids within human health systems.

Conclusion

The synthesis of evidence from 32 peer-reviewed studies demonstrates that the bioavailability and physiological functions of palm oil-derived carotenoids are governed by a coordinated interaction between intestinal absorption mechanisms, food matrix characteristics, and provitamin A conversion efficiency. These three components operate as an integrated system rather than as independent determinants, collectively shaping the extent to which carotenoids are absorbed, metabolized, and utilized within the body. At the digestive level, efficient micellar incorporation and lipid-assisted solubilization are identified as fundamental processes that enable carotenoids to transition from dietary intake into bioaccessible forms. The presence of dietary lipids and bile-mediated emulsification enhances the formation of mixed micelles, thereby facilitating transporter-mediated uptake across the intestinal epithelium. Variations in these processes contribute directly to differences in absorption efficiency, highlighting the importance of physiological and dietary conditions in determining carotenoid availability.

The role of the food matrix further modulates these outcomes by influencing the release, stability, and dispersion of carotenoids during digestion. Lipid-rich matrices, such as those naturally associated with palm oil, provide favorable conditions for carotenoid solubilization and absorption. At the same time, matrix complexity, including the presence of dietary fiber, protein interactions, and processing conditions, can either enhance or limit bioavailability depending on the structural and compositional context of the food system. At the metabolic level, the conversion of provitamin A carotenoids into retinol represents a critical step linking bioavailability to physiological function. This process is influenced by enzymatic activity, particularly β-carotene monooxygenase 1, as well as by upstream factors related to absorption efficiency. Variability in conversion ratios reflects differences in both metabolic capacity and substrate availability, reinforcing the interconnected nature of absorption and conversion processes.

Collectively, these findings indicate that carotenoid functionality is determined by a sequential and interdependent pathway in which digestive release, micellar transport, and enzymatic conversion act in concert. Limitations at any stage of this pathway may reduce overall bioavailability, whereas favorable conditions across all stages can significantly enhance physiological outcomes. This integrated perspective provides a comprehensive explanation of how carotenoid bioavailability translates into functional effects, including contributions to vitamin A status and oxidative balance. The evidence further highlights that variability in reported outcomes is an inherent characteristic of carotenoid research, arising from differences in experimental models, dietary composition, and individual physiological factors. Despite this variability, a consistent pattern emerges in which optimized lipid environments and appropriate matrix conditions support improved absorption and metabolic utilization. These observations underscore the importance of considering both biological mechanisms and dietary context when evaluating the nutritional relevance of carotenoids. In a broader nutritional framework, palm oil-derived carotenoids represent a viable source of bioactive compounds that can contribute to physiological functions when consumed within balanced dietary systems. The findings support a neutral and evidence-based perspective, indicating that their effectiveness is contingent upon the interaction of multiple factors rather than a single determinant.

This reinforces the need for integrative approaches in both research and dietary application. Future research directions should prioritize the expansion of human-based evidence, particularly through well-controlled intervention studies that account for inter-individual

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variability, genetic factors, and long-term physiological outcomes. In addition, further investigation into food processing strategies and formulation techniques may provide opportunities to enhance carotenoid bioavailability and optimize their functional contribution. Strengthening methodological consistency across studies will also be essential to improve comparability and advance the overall understanding of carotenoid metabolism. Overall, the integrated analysis confirms that the bioavailability and physiological functions of palm oil-derived carotenoids are the result of interconnected processes spanning digestion, matrix interaction, and metabolic conversion. This coordinated framework offers a comprehensive basis for understanding carotenoid utilization and supports the development of more effective nutritional strategies grounded in mechanistic evidence.

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